

Deviation of the Nucleon Shape From Spherical Symmetry: Experimental Status

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Abstract. In this brief pedagogical overview the physical basis of the deviation of the nucleon shape from spherical symmetry will be presented along with the experimental methods used to determine it by the $\gamma^*p \rightarrow \Delta$ reaction. The fact that significant non-spherical electric(E2) and Coulomb quadrupole(C2) amplitudes have been observed will be demonstrated. These multipoles for the N, Δ system as a function of Q^2 from the photon point through 4 GeV^2 have been measured with modest precision. Their precise magnitude remains model dependent due to the contributions of the background amplitudes, although rapid progress is being made to reduce these uncertainties. A discussion of what is required to perform a model independent analysis is presented. All of the data to date are consistent with a prolate shape for the proton (larger at the poles) and an oblate shape(flatter at the poles) for the Δ . It is suggested here that the fundamental reason for this lies in the spontaneous breaking of chiral symmetry in QCD and the resulting, long range(low Q^2), effects of the pion cloud. This verification of this suggestion, as well as a more accurate measurement of the deviation from spherical symmetry, requires further experimental and theoretical effort.

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1 Introduction

Experimental confirmation of the deviation of the proton structure from spherical symmetry is fundamental and has been the subject of intense experimental and theoretical interest[1] since this possibility was originally raised by Glashow[2]. The most direct method to determine this would be to measure the quadrupole moment of the proton. However since the proton spin is $1/2$ this is not possible. Therefore, this determination has focused on the measurement of the electric and Coulomb quadrupole amplitudes (E2, C2) in the predominantly M1 (magnetic dipole-quark spin flip) $\gamma^*N \rightarrow \Delta(1/2 \rightarrow 3/2)$ transition. Thus measurements of the E2 and C2 amplitudes represent deviations from spherical symmetry of the N, Δ system and not the nucleon alone. The experimental difficulty is that the E2/M1 and C2/M1 ratios are small (typically $\simeq -2$ to -8% at low Q^2). In this case the non-resonant (background) and resonant quadrupole amplitudes are the same order of magnitude. For this reason experiments have to be designed to attain the required sensitivity and precision to separate the signal and background contributions. This has been accomplished for photo-pion reactions for the E2 amplitude using polarized photon beams[3,4]. In pion electroproduction the deviation from spherical symmetry is easier to observe due to the interference between

the longitudinal(Coulomb) C2 and the dominant M1 amplitudes by observation of the σ_{TL} cross section[5]. Electroproduction experiments are also being performed for a range of four momenta Q^2 [5,6,7,8,9,10,11,12,13] which provides a measure of the spatial distribution of the transition densities. On the other hand the presence of the additional longitudinal multipoles in electroproduction means that there are more observables to measure and therefore more data must be taken than in photoproduction experiments. The experiments to generate an extensive data-base that would allow a model independent analysis have just begun, both in photo- and in electro-production. At the present time one must rely on reaction models to extract the resonant M1, E2, and C2 amplitudes of interest from the data. As has been pointed out the model error can be much larger than the experimental error[5]. Therefore it is important to test model calculations for a range of center of mass(CM) energies W in the region of 1232 MeV, the resonant energy, which provides a range of the relative background and resonant amplitudes, as well as picking out specific observables which are sensitive to the quadrupole amplitudes (e.g. σ_{TL}) and others which are primarily sensitive to the background amplitudes(e.g. $\sigma_{TL'}$).

^a Expanded version of an Invited talk at Electron-Nucleus Scattering VII, June 23-28,2002, Elba, Italy.

2 Why Should the Nucleon be Deformed?

It is well known that in the quark model there are non-central (tensor) interactions between quarks which were modeled after the electromagnetic interaction[2,14].

Although this interaction does, in fact, introduce non-spherical responses (E2 and C2) into the electromagnetic matrix elements they are only a small fraction of the observed amplitudes. In my view this is not surprising since the long distance part of the nucleon and Δ structure should be related to the pion cloud which is poorly represented in quark models. We expect the long range (low Q^2) behavior to be pion field dominated since it is the lightest hadron. Of course this is well known experimentally and is a cornerstone of classical nuclear theory. What is new is our more recent understanding that the pion itself, and its interaction with other hadrons, is a consequence of spontaneous chiral symmetry breaking in QCD[15]. In the chiral limit, i.e. where the light quark masses are set equal to zero, the QCD Lagrangian has chiral symmetry which does not appear in nature. We know this experimentally since if chiral symmetry were exact we would observe parity doubling of all hadronic states. This means that the chiral symmetry is broken (or more exactly hidden) and is manifested in the appearance of zero mass, pseudoscalar Goldstone Bosons. Since, in nature, the light quark masses are small but non-zero, the physical Goldstone Bosons have a small mass and are identified as the π mesons. The coupling of a Goldstone Boson to a nucleon is $g\sigma \cdot \mathbf{p}$ where g is the $\pi - N$ coupling constant (predicted by the Goldberger-Trieman relation) σ is the nucleon spin, and \mathbf{p} is the pion momentum. This interaction vanishes in the s wave and leads to the Goldstone theorem that the interaction vanishes as $p \rightarrow 0$. The $\sigma \cdot \mathbf{p}$ interaction is strong in the p wave which leads to the Δ resonance and is the basis of the deviation from spherical symmetry in the nucleon, illustrated schematically in Fig. 1, and Δ structure. In a sense this is the basis of classical nuclear theory.

Although it is beyond the scope of this presentation, I cannot resist mentioning that the $\sigma \cdot \mathbf{p}$ interaction required by the spontaneous breakdown of chiral symmetry in QCD economically describes the basics of πN scattering and of nuclear physics. Indeed, this πN interaction leads to a non-spherical NN interaction (the tensor force). By generalizing Fig. 1 to the case of two nucleons, it is not hard to see physically (semi-classically) that the most attractive position for two nucleons is for one nucleon to be spatially above the second with their spins parallel. This is the configuration which is favored by the tensor force.

Quantitatively the quark model calculations of the M1 matrix element are too small[16](although this is not often discussed). This is shown in Table 1 where the magnitude of the experimental[18] and theoretical matrix elements for the $\gamma N \rightarrow \Delta$ reaction are presented. It can be seen that the quark model predictions are $\simeq 30\%$ too low for the dominant M1 and an order of magnitude too small for the E2 matrix element, which is the indicator of the non-spherical structure of the nucleon and Δ structure. The table also includes the redundant E2/M1 ratio just to illustrate that it has become commonplace in the recent

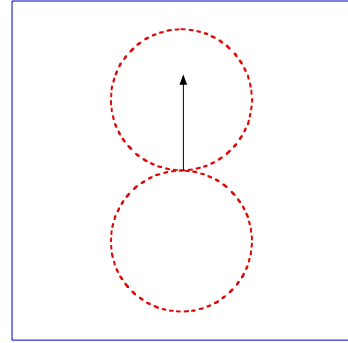


Fig. 1. The pion cloud contribution to nucleon structure. The arrow represents the nucleon spin vector and the dotted line the pion cloud.

literature to quote only this latter ratio and not the absolute values of the matrix elements. By doing so, some important lessons tend to be overlooked. As an example, we focus on the quark model extensions[17], which introduce multi-body interactions between the quarks, taking into account the composite nature of the constituent quarks. These currents take the pion field partially into account and, as can be seen in Table 1, this effect increases the E2 matrix element to the empirical size and in fact increases the E2/M1 ratio to an even larger value than the experiment. However this treatment does not increase the magnitude of the M1 matrix element so it remains $\simeq 30\%$ less than experiment. As was discussed above, based on spontaneous chiral symmetry breaking, it is physically intuitive that this shortfall should be looked for in the long range effect of the pion cloud.

This issue of the quark core and pion cloud contributions has been addressed in a meson exchange model by Sato and Lee[19]. Their model results are also presented in Table 1. Here it is seen that their model tends to make up for the deficiencies of the quark model, not only for the E2/M1 ratio, but for the individual magnitudes of the E2 and M1 matrix elements. The uncertainties shown in Table 1 are due to uncertainties in their model parameters (see Table IV and the discussion in their 1996 paper[19]). Sato and Lee have also calculated the effects of the pion cloud for pion electroproduction as a function of Q^2 and the results are presented in Fig. 2. It can be seen that the enhancement of the M1 matrix element is significant and that the non-spherical E2 and C2(Coulomb quadrupole) matrix elements are dominated by meson cloud effects. It is also seen in Fig. 2 that, as expected, the long range pion cloud effects are more dominant at low Q^2 . The dynamic Sato-Lee calculations are in excellent agreement with the data for photo-pion production in the Δ region (some of the parameters were fit to these data) and are also in good agreement with the JLab data presented by Burkert at this meeting. However, before becoming complacent, we should note that the next section will show that this model is not in agreement with low Q^2 data taken at Bates[5,7] near the predicted peak of the pion cloud contribution. This suggests to me that

Table 1. Experimental and Model Amplitudes for the $\gamma N \rightarrow \Delta$ Reaction. The units for M1 and E2 are $10^{-3} \text{GeV}^{-1/2}$ and E2/M1 in % The numbers in parenthesis are experimental or model errors

model	M1	E2	E2/M1
Experiment[18]	288(8)	-7.2(0.5)	-2.5(0.5)
QM:Capstick[16]	196	-0.1	-0.04
QM:Buchmann[17]	203	-7.0	-3.5
SL(bare)[19]	175	0.0(2.3)	0.0(1.3)
SL(dressed)[19]	258	-4.6(2.3)	-1.8(0.9)

even though the Sato-Lee Lagrangian has chiral symmetry they are not completely implementing the dynamics of chiral symmetry breaking, perhaps in their omission of the pion loops which are required in chiral perturbation theory calculations of the $ep \rightarrow e\pi^0 p$ reaction in the near threshold[20] and Δ regions[21]. Therefore, even though the contribution of the pion cloud appears to be required, its description must be considered somewhat qualitative at this point. It's detailed contribution needs to be calculated in a manner which is more consistent with the dynamics of spontaneous breaking.

Calculations of the $\gamma^* N \rightarrow \Delta$ transition in chiral perturbation theory (ChPT), which incorporates spontaneous chiral symmetry breaking in a manner which is consistent with QCD, have just begun[21]. In this calculation the Δ is included as a dynamical degree of freedom. A low energy expansion has been performed in the small parameter $\epsilon = (p_\pi, m_\pi, \delta = M_\Delta - M_p)$ to order $O(\epsilon^3)$. In this calculation the importance of the pion loops is clear since they are required by the power counting rules of ChPT at $O(\epsilon^3)$, or higher. As is typical of low energy effective theories there are two low energy parameters which were fit to the empirical M1 and E2 transitions so that there aren't any predicted values to be included in Table 1. The slopes of the transition form factors are predicted, but cannot yet be compared to experiment since there is a paucity of low Q^2 data, which is something that we plan to remedy in the next year. On the theoretical side it is important that the ChPT calculations be carried out to make contact with experimental observables and also extended to $O(\epsilon^4)$ to check the convergence of these calculations. It is clear that at the present time the verification of the idea that the pion cloud is the major contributor to the nucleon and Δ deformation requires more theoretical and experimental work. This is important, since as was stated above, it is expected that the pion cloud plays a significant role in baryon structure[22].

The question of the shape of the nucleon and Δ were explored in the context of three different models by Buchmann and Henley[23]. They conclude that the proton is prolate (longer at the poles) and the Δ is oblate (flatter at the poles). This is consistent with the data.

Finally we note that there are two lattice QCD calculations at $Q^2 = 0, 0.52 \text{GeV}^2$ which demonstrate non-zero quadrupole transition amplitudes. Taking into account the relatively large theoretical errors, as well as the experimental errors, they are tolerably close to the data. Clearly we await fur-

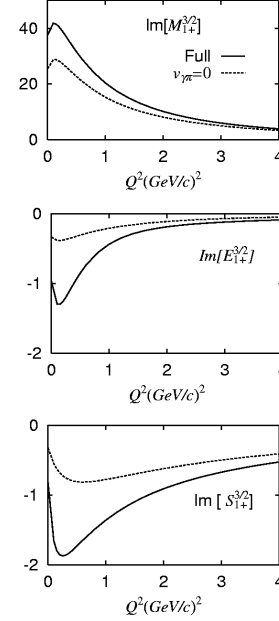


Fig. 2. The contribution of the quarks and pion cloud to the M1, C2, and E2 transition amplitudes in the $\gamma^* p \rightarrow \Delta$ reaction calculated by Sato and Lee[19]

ther calculations which reduce the error, so that accurate QCD calculations can be compared to experimental results. We do note however that the question of exactly how to compare the experimental transition amplitudes, which contain background continuum contributions, and a theoretical calculation which assumes that the Δ is a bound particle, need improvement.

3 Experiments on Proton Deformation

Modern photon experiments have been carried out at Mainz [3] and Brookhaven[4] of the $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ n$ reactions with polarized photons. The combination of accurate measurements and the use of polarized photons provides sufficient sensitivity so that two laboratories have reported measurements of both the small E2 amplitude and the dominant M1 amplitude. The observation of both charge channels allows an isospin separation of the resonant $I = 3/2$ channel. The results for the polarized photon asymmetry are presented in Fig. 3. There is good agreement for this quantity between the two labs and model calculations and the results are $E2/M1 = -2.5 \pm 0.5\%$ [18] showing that there is significant deformation in the N, Δ system (see the discussion in[4]). It should be mentioned, however, that although there is very good agreement between the Mainz and Brookhaven measurements of the polarized photon asymmetries shown in Fig. 3, there is a significant deviation in the unpolarized cross sections[3,4] which unfortunately is still unresolved.

The situation for pion electroproduction in the Δ resonance region is evolving rapidly with activity at all the intermediate energy facilities: Bates[5,6,7], Mainz[8,9], Bonn[10],

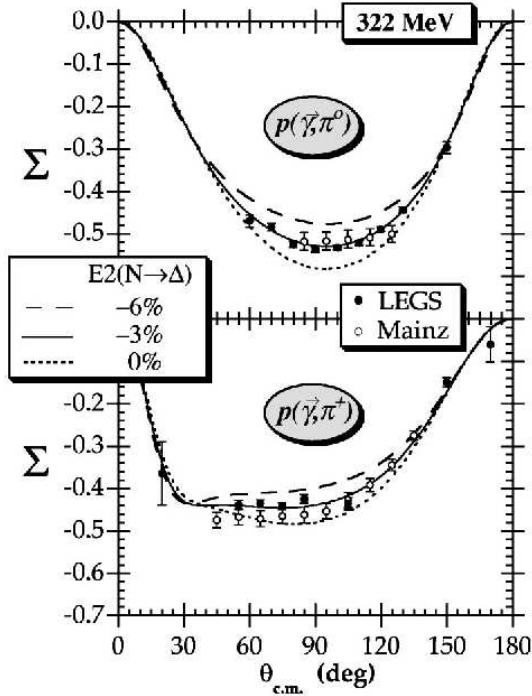


Fig. 3. Polarized photon asymmetries for the $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ n$ reactions plotted versus θ . The curves are MAID[26] for different E2/M1 ratios as shown.

and JLab[11,12,13] (for a review see[1]). In this brief report only a few highlights will be mentioned. The work at Bates will be emphasized here since the focus of this talk is on the pion cloud effects which are largest in the low Q^2 regime covered by those experiments and also since the JLab work was covered by Burkert at this meeting[24]. There has been a corresponding increase in the theoretical activity in this field which is being emphasized in a complementary talk at this meeting by Tiator who also presents an overview of the data[25]. The goal of the pion electroproduction experiments is to obtain accurate data which have sufficient sensitivity to determine the M1, E2, and C2 resonance amplitudes, but also sufficient coverage to determine the background amplitudes which are of the same order of magnitude as E2 and C2. These are of interest in their own right as an integral part of the $\gamma\pi N$ system and therefore as part of the chiral structure of matter. For example, the resonance and background amplitudes are related to the form factors and to the electric and magnetic polarizabilities of the nucleon. The background amplitudes contribute to the cross sections linearly with the resonance amplitudes, and the interference terms therefore make significant contributions to the observables. The background contributions also occur in the resonance amplitudes and are part of the physics. In a sense this is a crucial difference between dynamic and static models(e.g.the quark model) for which the Δ is treated as a bound state, which ignores the background contributions. The cleanest experimental determination would consist of an empirical multipole analysis of the data. At the present time we

do not have a sufficient, accurate data-base with which to perform such an analysis and must rely on empirical models to extract the resonant amplitudes. The present short term experimental goal is to provide a sufficiently sensitive and accurate data-base to rigorously test the models. It is hoped that the combination of Born terms and the tails of higher resonances will suffice to reproduce the background amplitudes.

The coincident $p(e, e'\pi)$ cross section in the one-photon-exchange-approximation can be written as [27]:

$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_\pi^{cm}} = \Gamma_v \sigma_h(\theta, \phi) \quad (1)$$

$$\begin{aligned} \sigma_h(\theta, \phi) = & \sigma_T + \varepsilon\sigma_L + \sqrt{2\varepsilon(1+\varepsilon)}\sigma_{TL} \cos\phi \\ & + \varepsilon\sigma_{TT} \cos 2\phi + hp_e \sqrt{2\varepsilon(1-\varepsilon)}\sigma_{TL'} \sin\phi \end{aligned}$$

where Γ_v is the virtual photon flux, $h = \pm 1$ is the electron helicity, p_e is the magnitude of the longitudinal electron polarization, ε is the virtual photon polarization, θ and ϕ are the pion CM polar and azimuthal angles relative to the momentum transfer \mathbf{q} , and σ_L , σ_T , σ_{TL} , and σ_{TT} are the longitudinal, transverse, transverse-longitudinal, and transverse-transverse interference cross sections, respectively. Each of these partial cross sections can be written in terms of the multipoles[27]. The E2 and M1 amplitudes can be obtained from a combination of σ_T and σ_{TT} as was done in photo-production (the polarized photon asymmetry $= \sigma_{TT}/\sigma_T$). In the approximation that only s and p wave pions are produced they can be written as[27]:

$$\sigma_T(\theta) = A_T + B_T \cos\theta + C_T \cos^2\theta \quad (2)$$

$$\sigma_{TT}(\theta) = \sin^2\theta A_{TT}$$

$$A_T \approx 5/2|M_{1+}|^2 + \text{Re}[M_{1+}M_{1-}^* - 3M_{1+}E_{1+}^*]$$

$$B_T \approx 2M_{1+}E_{0+}^*$$

$$C_T \approx -3/2|M_{1+}|^2 + \text{Re}[9M_{1+}E_{1+}^* - 3M_{1+}M_{1-}^*]$$

$$A_{TT} \approx -1/2|M_{1+}|^2 - \text{Re}[M_{1+}E_{1+}^* + M_{1+}M_{1-}^*]$$

where the pion production multipole amplitudes are denoted by $M_{l\pm}$, $E_{l\pm}$, and $L_{l\pm}$, indicating their character (magnetic, electric, or longitudinal), and their total angular momentum ($J=l \pm 1/2$)[28]. The expressions for A_T , B_T , C_T and A_{TT} are in the truncated multipole approximation where it is assumed that only terms which interfere with the dominant magnetic dipole amplitude M_{1+} are kept. The exact formulas without this approximation can be found in [27]. In this approximation the longitudinal cross section $\sigma_L = 0$. In model calculations[19,26,30,31,32] this approximation is not made and significant deviations from the truncated multipole approximation occur.

The C2 amplitude can be obtained from σ_{TL} . An example of this is presented in Fig.4 which shows the Bates data[5] and the difference between the cross section with and without the quadrupole C2 amplitude calculated with the MAID model[26]. The sensitivity is quite large, again indicating a significant d state component in the N, Δ system. As can be seen from a comparison of Figs. 3 and 4, there is far more sensitivity to the C2 as compared to the E2 amplitude, despite the fact that they are both only a

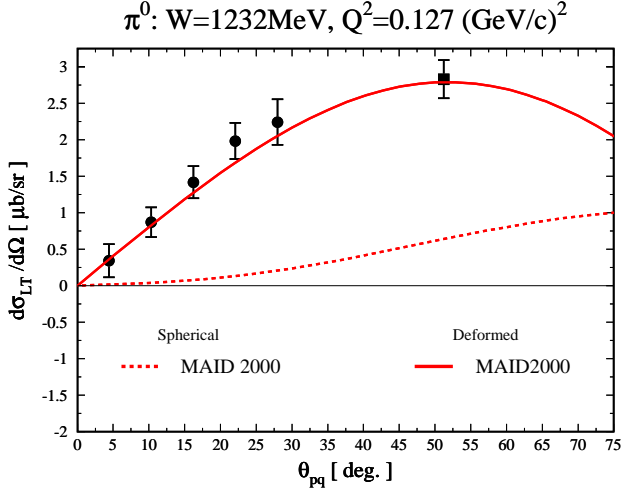


Fig. 4. The differential cross section for the $ep \rightarrow e' \pi^0 p$ reaction plotted versus θ_{pq} , the CM angle of the proton relative to the momentum transfer \mathbf{q} (the pion CM angle = $180^\circ - \theta_{pq}$) [5, 7]. The curves are from the MAID model [26] with and without the C2 contribution.

few % of the M1 amplitude. The reason for this difference lies in the fact that in the longitudinal amplitude the C2 is a leading term, whereas in the transverse amplitude the E2 occurs in a linear combination with the M1 amplitude.

The TL' and the TL (transverse-longitudinal) response functions are the real and imaginary parts of the same combination of interference multipole amplitudes. Again assuming that only s and p wave pions are produced they can be written as [27]:

$$\begin{aligned}\sigma_{TL}(\theta) &= -\sin\theta \text{Re}[A_{TL} + B_{TL} \cos\theta] \\ \sigma_{TL'}(\theta) &= \sin\theta \text{Im}[A_{TL} + B_{TL} \cos\theta] \\ A_{TL} &\approx -L_{0+}^* M_{1+} \\ B_{TL} &\approx -6L_{1+}^* M_{1+}\end{aligned}\quad (3)$$

where the last two approximations are for the truncated multipole approximation.

The Bates out-of-plane spectrometer system (OOPS) [29] which was designed and built in order to exploit the ϕ dependence shown in Eq. 2 is shown schematically in Fig. 5. It consists of an electron spectrometer used in conjunction with four relatively light spectrometers which can be deployed at a fixed polar angle θ_{hq} , relative to the momentum transfer \mathbf{q} to detect the charged, emitted hadron (p, π^+). By deploying multiple (3 or 4) spectrometers at different azimuthal angles ϕ , the combination of $\sigma_0 = \sigma_T + \epsilon\sigma_L, \sigma_{TT}$ and σ_{TL} can be simultaneously measured in one run, which reduces the systematic errors caused by luminosity measurement errors. Furthermore, the geometry is optimized to measure relatively small relative magnitudes of σ_{TL}/σ_0 and σ_{TT}/σ_0 . The combination of high luminosity and small systematic errors, allows precise measurements to be performed. Furthermore, when polarized electron beams are employed, measurements of the fifth structure function $\sigma_{TL'}$, which require out-of-plane hadron detection, become possible.

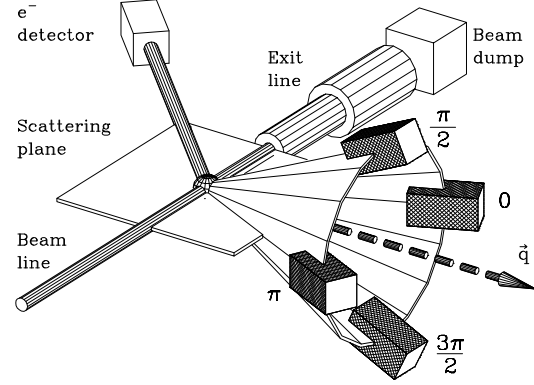


Fig. 5. A schematic diagram of the out-of-plane spectrometer system (OOPS) at Bates. See text for discussion

Several rounds of experiments have been carried out at Bates with the OOPS apparatus [5, 7]. Experiments have been carried out at $Q^2 = 0.127 \text{ GeV}^2$ over a range of CM energies W , below, on, and above the Δ resonance energy $W = 1232 \text{ MeV}$. For brevity only the results at the Δ peak are presented in Fig. 6. The experimental results are compared to calculations [19, 26, 30, 31, 32]. The most ambitious calculations are the dynamical Sato-Lee model [19] and a dispersion relation calculation [31]. The Sato-Lee model calculates all of the multipoles and $\pi - N$ scattering from dynamical equations. Dispersion relation calculations have previously provided good agreement with photo-pion production data [33]. Unfortunately, neither of these calculations agrees with the Bates data. The Sato-Lee model [19] agrees for the unpolarized cross sections $\sigma_0 = \sigma_T + \epsilon\sigma_L$ but is in strong disagreement with the measurements of σ_{TL} and $\sigma_{TL'}$. The dispersion relations calculation [31] agrees with some of the Bates data but disagrees with the measurement of σ_0 at $W = 1170 \text{ MeV}$ (not shown here) and with σ_{TL} measurements. Only the two most empirical models [26, 32] give reasonable overall fits to all of the Bates data. The Mainz Unitary Model (MAID) is a flexible way to fit observed cross sections as a function of Q^2 [26]. It incorporates Breit-Wigner resonant terms, Born terms, higher N^* resonances, and is unitarized using empirical $\pi - N$ phase shifts. The fitted parameters of the model include a range of data [26]. The SAID calculation [32] is an empirical multipole fit to previous electropion production data. The Kamalov-Yang model [30] includes dynamics for the resonant channels and uses the background amplitudes of the MAID model. This model is in reasonable agreement with most of the Bates data with the exception of the unpolarized cross section σ_0 at $W = 1170 \text{ MeV}$ (not shown here).

The Sato-Lee dynamical model [19] predicts that the pion cloud is the dominant contribution to the quadrupole amplitudes at low values of Q^2 . Unfortunately, this model is not in agreement with our data but showed much better predictions of the recently reported result from the CLAS detector at JLab for the $p(e, e'p)\pi^0$ reaction in the

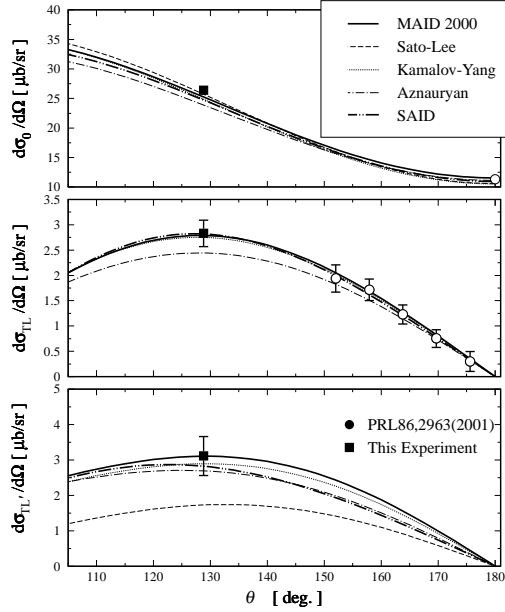


Fig. 6. Cross sections for the $p(e, e'p)\pi^0$ reaction for $W = 1232$ MeV, $Q^2 = 0.127$ (GeV/c) 2 plotted versus θ . The top panel is for $\sigma_0 = \sigma_T + \epsilon\sigma_L$. The middle panel is for σ_{TL} and the bottom panel is for $\sigma_{TL'}$. The curves are MAID[26] (solid), Sato-Lee[19] (dashed), Kamalov et al[30] (dotted), dispersion theory[31] (dot-dashed), and empirical multipole fit to previous pion electroproduction data(SAID)[32] (long-dashed).

Δ region for Q^2 from 0.4 to 1.8 (GeV/c) 2 [11]. This seems to indicate that the dominant meson cloud contribution, which is predicted to be a maximum near our values of Q^2 , is not quantitatively correct.

Recently, a measurement of $A_{TL'}$ for the $p(e, e'p)\pi^0$ reaction in the Δ region was performed at Mainz[9]. The kinematics include a range of Q^2 values from 0.17 to 0.26 (GeV/c) 2 and backward θ angles. These data were compared to several models[19, 26, 30] which all disagreed with the data. The results of the MAID calculation had to be multiplied by 0.75 to agree with the experiment[9]. In comparison with the Bates $\sigma_{TL'}$ data[7], if one multiplies the MAID results by the same factor these data are still in agreement at $W=1170$ MeV, but at $W=1232$ MeV they do not agree with a discrepancy of 1.4σ . Therefore a reduction of 25% in the MAID predictions for $\sigma_{TL'}$ does not seriously effect the agreement with the Bates experiment.

It is of interest to compare the TL and TL' results presented here with those of the recoil polarizations which are proportional to the real and imaginary parts of interference multipole amplitudes. For the $p(e, e'p)\pi^0$ channel the outgoing proton polarizations have been observed in parallel kinematics (the protons emitted along \mathbf{q} or $\theta = 180^\circ$) [6, 8]. For this case the observable amplitudes are[27]:

$$\begin{aligned} \sigma_0 p_x &\propto \text{Re}[A_{TL}^x] \\ \sigma_0 p_y &\propto \text{Im}[B_{TL}^y] \\ \sigma_0 p_z &\propto \text{Re}[C_{TT}^z] \end{aligned} \quad (4)$$

$$\begin{aligned} A_{TL}^x &\approx B_{TL}^y \approx (4L_{1+}^* - L_{0+}^* + L_{1-}^*)M_{1+} \\ C_{TT}^z &\approx |M_{1+}|^2 + \text{Re}[(6E_{1+}^* - 2E_{0+}^*)M_{1+}] \end{aligned}$$

where σ_0 is the unpolarized cross section and the constants of proportionality contain only kinematic factors. The formulas for $A_{TL}^x, B_{TL}^y, C_{TT}^z$ assume s and p wave pions are produced and are in the truncated multipole approximation. This shows both the similarity and detailed difference between a measurement of TL and TL' and the recoil polarizations. In the published papers the data were compared to the MAID model which is not in good agreement with the data [6, 8]. At the present time we do not have sufficient data to pin down the multipoles which are responsible for this difference.

The EMR and CMR ratios as a function of Q^2 were presented by Tiator at this workshop[25]. For completeness these are included here as Figs. 7 and 8. The results have provided us with a reasonably consistent overall picture of the EMR and CMR ratios. Although not presented here the pion cloud models[19, 30] are not in agreement with the data shown in Figs. 7 and 8 (see e.g. the figure presented by Burkert[24]). This agrees with the observation that this model[19] does not agree with the data near $Q^2 = 0.125 \text{ GeV}^2$ as discussed above. In this connection it should be noted that there is a paucity of data between the photon point and $Q^2 = 0.4 \text{ GeV}^2$. We are planning to perform an experiment at Mainz to study this region where the pion cloud effects are predicted to be large[19, 30] to test the idea of pion cloud dominance of the E2 and C2 transition amplitudes at low Q^2 .

At large (asymptotic) values of Q^2 it is predicted that due to helicity conservation $EMR = E_{1+}/M_{1+} \rightarrow 1$ and that $CMR = S_{1+}/M_{1+} \rightarrow \text{constant}$ [35]. At the highest measured values of $Q^2 = 4 \text{ GeV}^2$ it is clear from Figs. 7 and 8 that the asymptotic QCD region has not been reached.

4 What Are the Requirements for a Model Independent Data Analysis?

It is interesting to consider how many data are required to perform a complete, model independent, multipole analysis. This can be illustrated in the approximation where it is assumed that only s and p wave pions are emitted (the discussion can be easily generalized without this assumption). In this case there are 7 multipoles for electroproduction ($E_{0+}, E_{1+}, M_{1\pm}, L_{0+}, L_{1\pm}$). Since these are complex they represent 14 numbers. However, an overall phase is irrelevant, so this leaves 13 numbers to be determined at each value of Q^2 and W . By counting the observables in Eqs. 2 and 3 it can be seen that for polarized electrons and unpolarized targets there are 8 observables, namely $A, B, C, A_{TT}, \text{Re}[A_{TL}], \text{Im}[A_{TL}], \text{Re}[B_{TL}], \text{Im}[B_{TL}]$ in Eqs 2 and 3. This is the number we have obtained at Bates (including data presently being analyzed) at $Q^2 = 0.127 \text{ GeV}^2$. By adding recoil polarization observables in parallel kinematics, 3 more numbers are measured (Eq. 4). This provides a stringent test of the reaction models but not enough

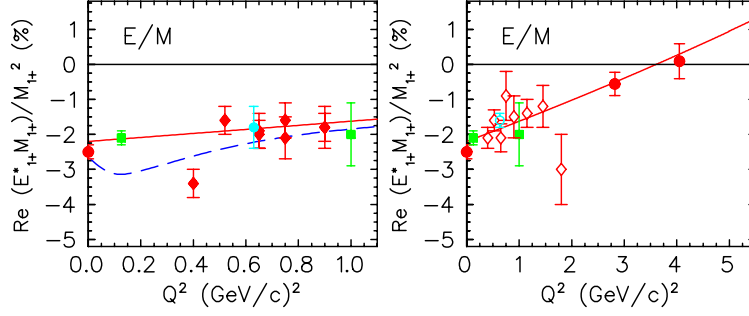


Fig. 7. The Q^2 dependence of the EMR ratio[25]. The solid and dotted curves are for MAID[26] and a dynamical model[30]. In the left panel the photon point is from Mainz[3], the point at $Q^2 = 0.125 \text{ GeV}^2$ is from Bates[5], the circle at $Q^2 = 0.63 \text{ GeV}^2$ is from Bonn[10], the point at $Q^2 = 1.0 \text{ GeV}^2$ is the MAID analysis[25] of the Hall A JLab data[13], and the points from $Q^2 = 0.4$ through 0.9 GeV^2 are from the truncated multipole analysis of the Hall B JLab data[11]. Note that for this latter set of data there are several points at the same value of Q^2 which correspond to data taken at two different beam energies. The dispersion of these points shows possible systematic errors in the data and analysis. The right hand panel shows the MAID analysis[25] of the same data points as in the left panel plus the highest Q^2 points[12]

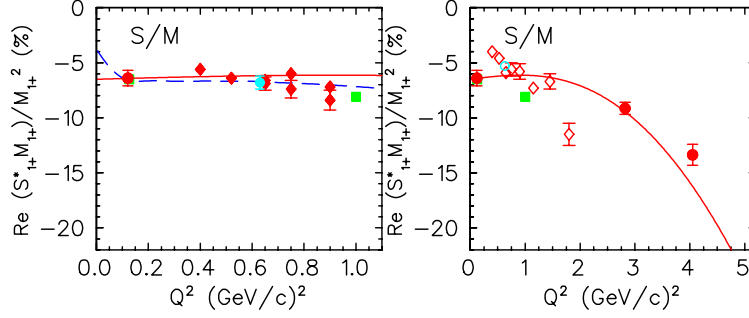


Fig. 8. The Q^2 dependence of the CMR ratio[25]. The points at $Q^2 = 0.125 \text{ GeV}^2$ are from the Mainz recoil polarization measurement(circle)[8] and the partially hidden square from Bates[5]. All the other points are from the same source as in Fig.7.

to make a model independent analysis. By measuring recoil polarization away from the forward direction the remainder can be measured. It is of interest to compare this to the photon experiments which have been carried out with polarized photons and unpolarized targets. There are 4 transverse multipoles which make $8-1 = 7$ numbers to determine. The actual experiments[3,4] determined 4 of these (A,B,C and A_{TT} of Eq. 2). So even these data are not yet sufficient for a model independent analysis, and polarized target data is required to complete this task. Such experiments are underway at LEGS in Brookhaven and are being planned at Mainz.

5 Conclusions

In conclusion, our data are consistent with a deviation of the nucleon and Δ from spherical symmetry. We are making rapid progress towards making a more quantitative measurement of this effect. The errors are primarily in the model extraction of the deformation. We also are making rapid progress towards stringently testing the reaction models, which means pinning down the resonant and background amplitudes. The latter effort consists of measure-

ments of the fifth structure function $\sigma_{TL'}$ and of the recoil polarizations. In addition we are also making progress towards a sufficient data-base to approach making model independent analyses. The interesting question of whether the main mechanism for the deviation from spherical symmetry has its origin in the spontaneous breaking of chiral symmetry in QCD with the resulting long range contribution from the pion cloud, needs further experimental and theoretical work.

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